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TECHNOLOGY FOR ORBITAL MULTI 100 KWe  
APPLICATIONS. VOLUME 1: EXECUTIVE SUMMARY  
(General Dynamics/Astronautics) 27 p

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# STUDY OF POWER MANAGEMENT TECHNOLOGY FOR ORBITAL MULTI-100KWe APPLICATIONS

VOLUME 1 • EXECUTIVE SUMMARY

July 15, 1980

**GENERAL DYNAMICS**  
*Convair Division*

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16. Abstract <p>This study examines mid-to-late 1980's power management technology needs to support development of a general purpose space platform, capable of supplying 100 to 250 KWe to a variety of users in LEO.</p> <p>To that end, a typical, Shuttle assembled and supplied space platform is illustrated, along with a group of payloads which might reasonably be expected to use such a facility.</p> <p>Examination of platform and user power needs yields a set of power system requirements used to evaluate power management options for life cycle cost effectiveness.</p> <p>The most cost-effective AC/DC and DC systems are evaluated, specifically to develop system details which lead to technology goals, including: array; and transmission voltage, best frequency for AC power transmission, and advantages and disadvantages of AC and DC system for this application.</p> <p>Finally, system and component requirements are compared with the state of the art to identify areas where technological development is required.</p>			
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## FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA Lewis Research Center (LeRC) in accordance with contract NAS 3-21757.

The principal results were developed throughout 1979 with reviews at LeRC on 8 May 1979, 31 July 1979, and 13 December 1979, and at NASA Headquarters on 22 January 1980.

Because of the scope of the study, many individuals contributed technical assistance. General Dynamics Convair personnel who significantly contributed to the study include:

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This executive summary is the first of three volumes comprising the total report. Volume two is a detailed discussion of the study results and volume three is a system requirements document for a 250KW space platform power management system.

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# 1

## INTRODUCTION

Space station studies have identified missions and configurations requiring a significant increase in electrical power compared to that of existing spacecraft. The power systems required for these missions represent a large step forward in physical size as well as electrical power. Recent space station studies (ref. 1 & 2) have concentrated on the candidate power sources and the load requirements, but have not defined the requirements for distribution and processing. Earlier power distribution and processing studies for aircraft and/or spacecraft (ref. 3-7) have indicated the general direction for technology advances. The recommended technology advances from these studies included the use of higher voltages, solid state power switching, automatic remote computer control, multiplexed control signals and continuous computer checkout. These advances are expected to yield significant improvements in reliability, weight, and cost. But these studies did not contain detailed information that is required to identify specific characteristics and technology needs for a space station. These characteristics and technology needs must be identified and developed so that they are available when needed for space station application. This study determines the necessary characteristics and technology needs of multihundred-KW power transmission, distribution, processing, and conditioning for cost effective, near-term, space station applications.

The study is divided into three separate tasks, and this report is divided into sections consistent with those tasks.

Basic system requirements were developed in Task 1, Part A. The large number of possible system topologies were sifted to select one or two of the most cost effective ones which satisfy the requirements. Cost effectiveness was considered to be a primary driver, here and throughout the study.

Detailed trade-offs were performed in Task 1, Part B, to select system operational parameters and provide component requirements and characteristics. Detailed life cycle costs were developed and a recommended system and an alternate were chosen. The chosen systems are evolved versions of those developed in Part A, with improvements based on the detailed analyses.

The state-of-the-art of the supporting technologies was assessed in Task 2, and compared to the component requirements to identify the areas where gaps exist. Efforts needed to close the gaps by the mid-to-late 1980s were then examined and cost and schedule estimates were provided in those areas where NASA must be active to assure a timely completion.

Each contract task described above was examined in detail in Task 3, and the technical details, results, conclusions, and recommendations for each work statement/work plan item are reported. Task 3 was organized in the same chronology as the contract work statement to ease evaluations and comparisons with requirements.



# 2

## STUDY RESULTS

### 2.1 TASK 1, PART A, SYSTEM ANALYSIS AND DEFINITION, ESTABLISHMENT OF APPROACHES.

This part of the study was performed as shown in Figure 2-1.

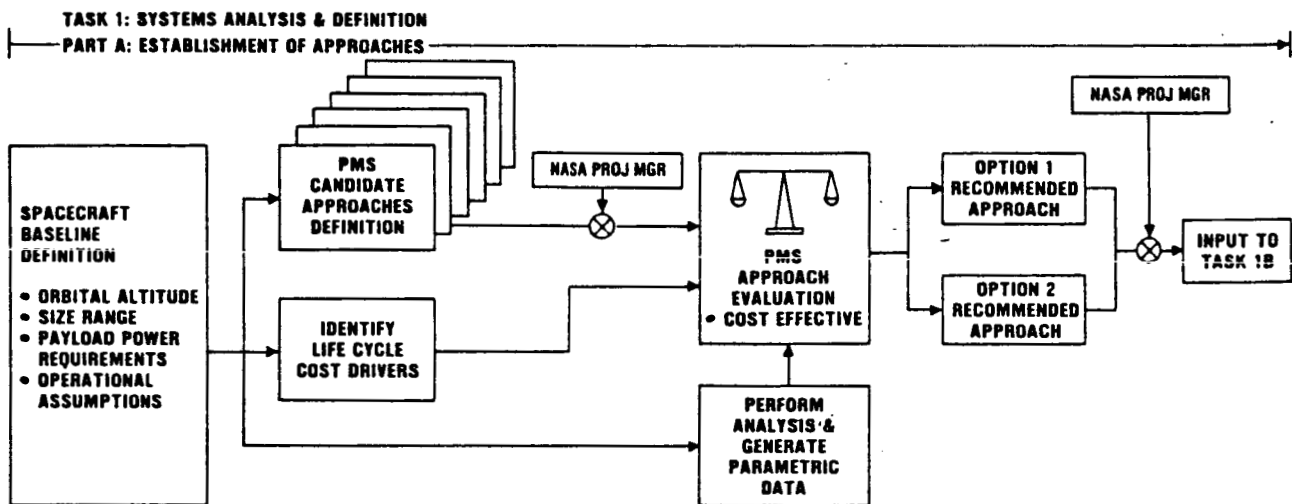


Figure 2-1. Task 1, Part A, Methodology.

**2.1.1 ESTABLISHMENT OF REQUIREMENTS.** The first step in examining the space power management problem for systems in the multi-100 KWe size range is to establish a real set of requirements, to which system topologies may be designed and against which system technical options may be measured. To that end, a low earth orbit (LEO), general-purpose space platform predesign has been developed as a typical user for a power management system (PMS) of this size and type. That satellite, with its important features, is pictured in Figure 2-2, and is shown during construction of a typical structure.

Evaluations of the power needs of each of the typical suite of payload modules pictured in Figure 2-2 has yielded the following major power requirements, distributed among 10 payload interfaces, in order to supply 250 KW average net power to the users.

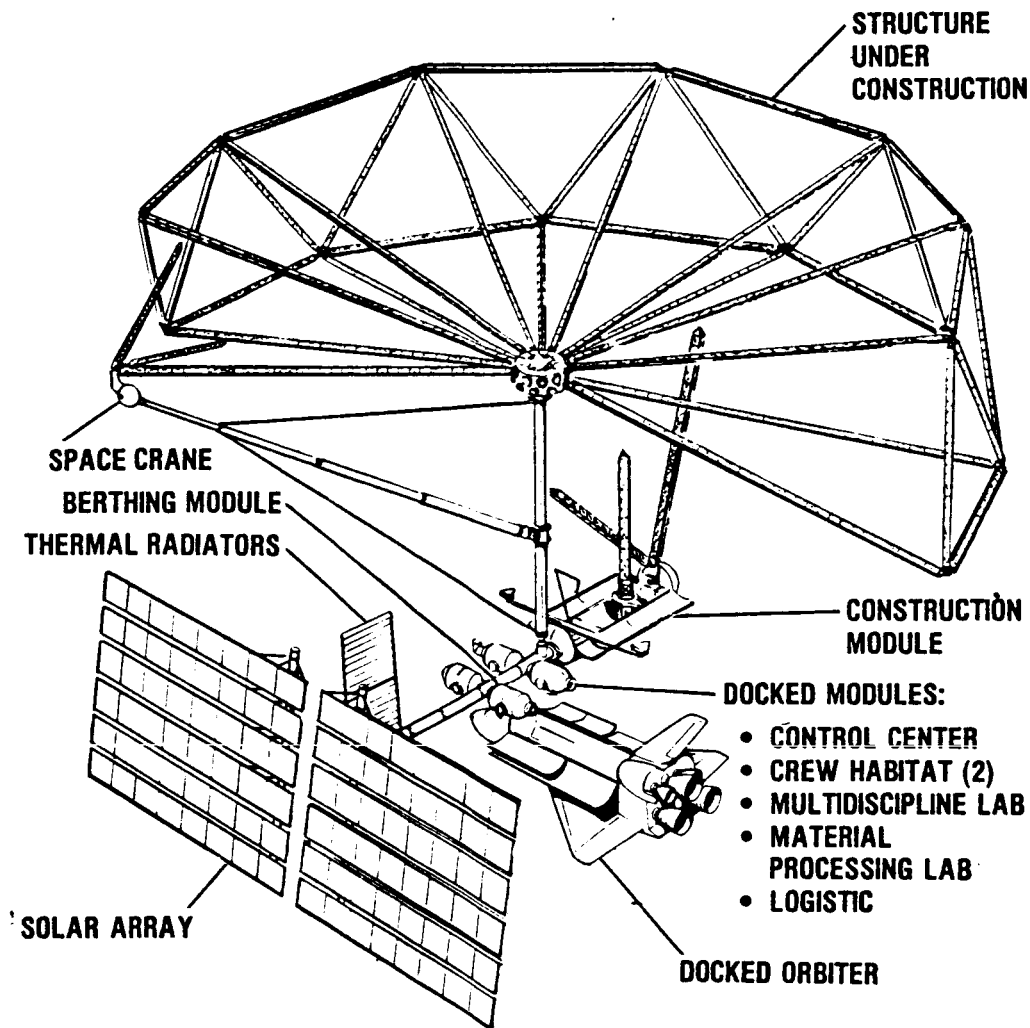


Figure 2-2. Baseline space platform configuration.

a. Total power capabilities (not simultaneously):

28 VDC	100 KW
115 VDC	100 KW
115 VAC RMS, 3 PHASE	100 KW
Unregulated	75 KW

b. Capabilities required to supply individual payload/module interface (maximum capability - ten locations):

28 VDC	15.0 KW
115 VDC	20.0 KW
115 VAC RMS, 3 PHASE	20.0 KW
Unregulated	75.0 KW

Other overall requirements affecting system design are listed below:

- a. Space platform in low earth orbit
- b. Mid-to-late 1980s technology readiness
- c. Ten year useful life
- d. Shuttle launch
- e. On-orbit maintenance/repair/retrieval capability
- f. Planar, silicon photovoltaic array
- g. Array and storage sizing based on continuous operation of load power in the range of 100-250 KWe (avg)
- h. Clean sheet approach — no combining of several smaller power systems
- i. Approach consistent with extended visits by man

For proper system evaluation, a more detailed specification is required. It needs to include quantities such as payload interface characteristics, physical sizes and equipment positions, typical load profiles, etc. Using the data from previous NASA studies, appropriate NASA specifications, and data from Convair in-house studies, such a detailed PMS specification was created and used for system synthesis and evaluation, and is contained in Volume 3 of this report.

**2.1.2 POWER MANAGEMENT SYSTEM CANDIDATES FOR PRELIMINARY EVALUATION.** Major candidates for overall system topologies may be broken down into two basic approaches or combinations of them. Briefly, they are:

- a. Centralized - Power storage, power conditioning, and switching functions are grouped and centrally located near the loads. The power source is treated as a single lumped element and connected to the power management unit with a transmission bus system. The four major classes of power are distributed to the individual payloads at non-isolated interfaces with a distribution bus system in the docking module.
- b. Distributed - The power source transmits its power to the docking module where it is distributed to each payload interface by a combined transmission/distribution bus system. Individual payload interface units, designed to operate with inputs at the transmission voltage levels, provide conditioned, controlled power at the values demanded by the individual payloads.

System considerations, such as AC transmission, DC transmission, voltage, frequency, number of phases, modularity, redundancy, adaptive control, etc., used with the basic choices above and combinations of them yielded approximately 80 possible system options. Those options were quickly reduced to about 16. Simple cost and technical tradeoffs were performed on these options to identify the one or two that held the most promise for cost effective 10-year missions.

The two systems thereby selected were:

- a. DC transmission with centralized regulation and control having the following main features:
  - (1) Hard wired DC array
  - (2) Slip rings for rotary joint power transfer
  - (3) Battery or fuel cell conditioning
  - (4) Centralized regulator unit
  - (5) Payload interface units containing only switching provisions for load isolation
  - (6) Single, high voltage DC power generation and transmission between solar array, batteries, and the central PMS unit
  - (7) Multiple bus, conditioned voltage distribution to the individual payload interfaces.
- b. AC transmission and distribution with distributed regulation and control having the following main features:
  - (1) Hard wired DC array
  - (2) Energy storage on array side of rotary joint, including battery or fuel cell conditioning
  - (3) Integrated inverter/regulator/rotary transformer
  - (4) High voltage, AC power transmission across rotary joint and throughout satellite
  - (5) Distributed power conditioning and isolation at each load interface unit

## 2.2 TASK 1, PART B, SYSTEM ANALYSIS AND DEFINITION, PMS REQUIREMENTS DEFINITION.

This study task was performed as shown in Figure 2-3.

Detailed trades were performed on the two system options selected to define their optimum operational parameters and to determine more accurate costs.

The major considerations addressed encompassed:

- a. System costs
- b. Size, weight, and performance
- c. AC or DC
- d. System voltages including arrays, batteries, transmission, and distribution.
- e. System frequencies including transmission for AC and converter internal frequencies.

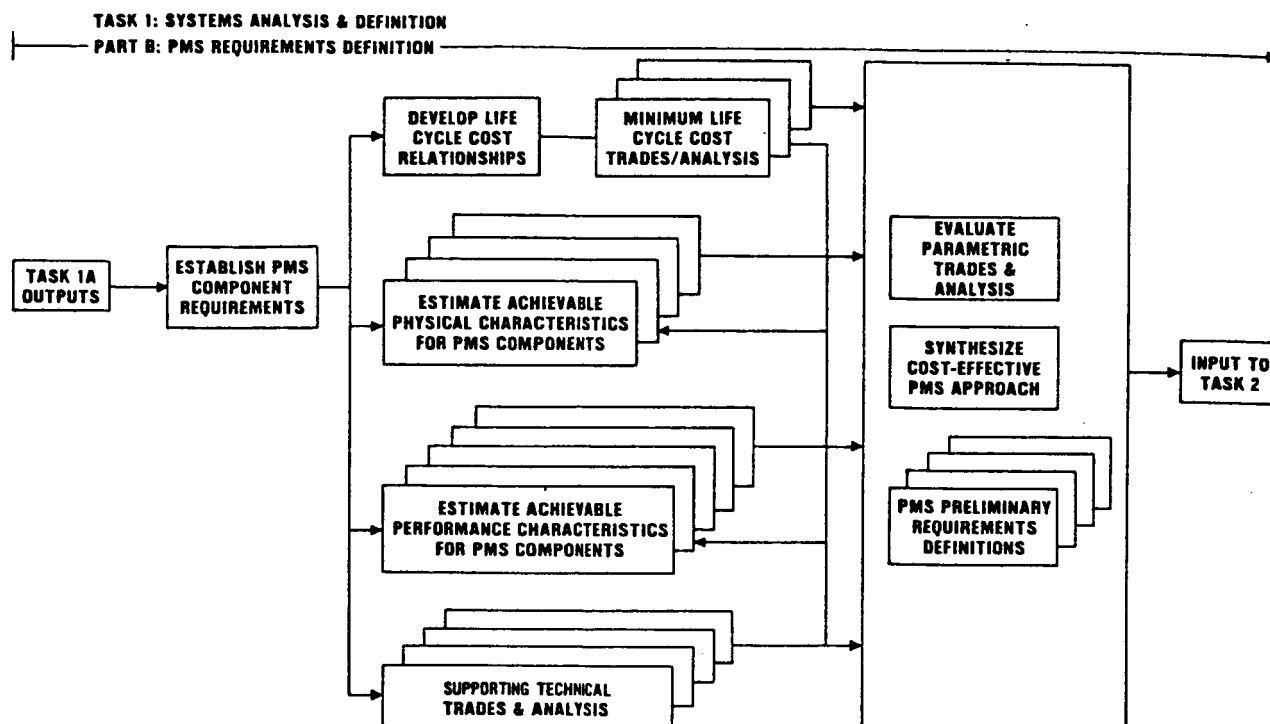


Figure 2-3. Task 1, Part B, Methodology.

Second-level considerations were evaluated for their system impact and they included the effects of:

- a. Load power range between 100 and 250 KW
- b. Peak power capabilities
- c. Transmission line length
- d. Ten year useful life
- e. Shuttle servicing capability in LEO
- f. Environmental excursions and cooling concepts
- g. Reliability
- h. Component accessibility and mechanical design
- i. Battery or fuel cell storage
- j. Conductor and grounding concepts
- k. Protection equipment and circuits
- l. Control methods
- m. EMI/EMC problems.

The performance of these tradeoffs and evaluations resulted in the recommendation that the first choice for a power management system for this kind of application and size range is a hybrid AC/DC combination (pictured in Figure 2-4). It has been optimized for life cycle costs, using a trade-off process which considered the parametric variations in hardware costs, testing, losses and efficiency, transportation to orbit,

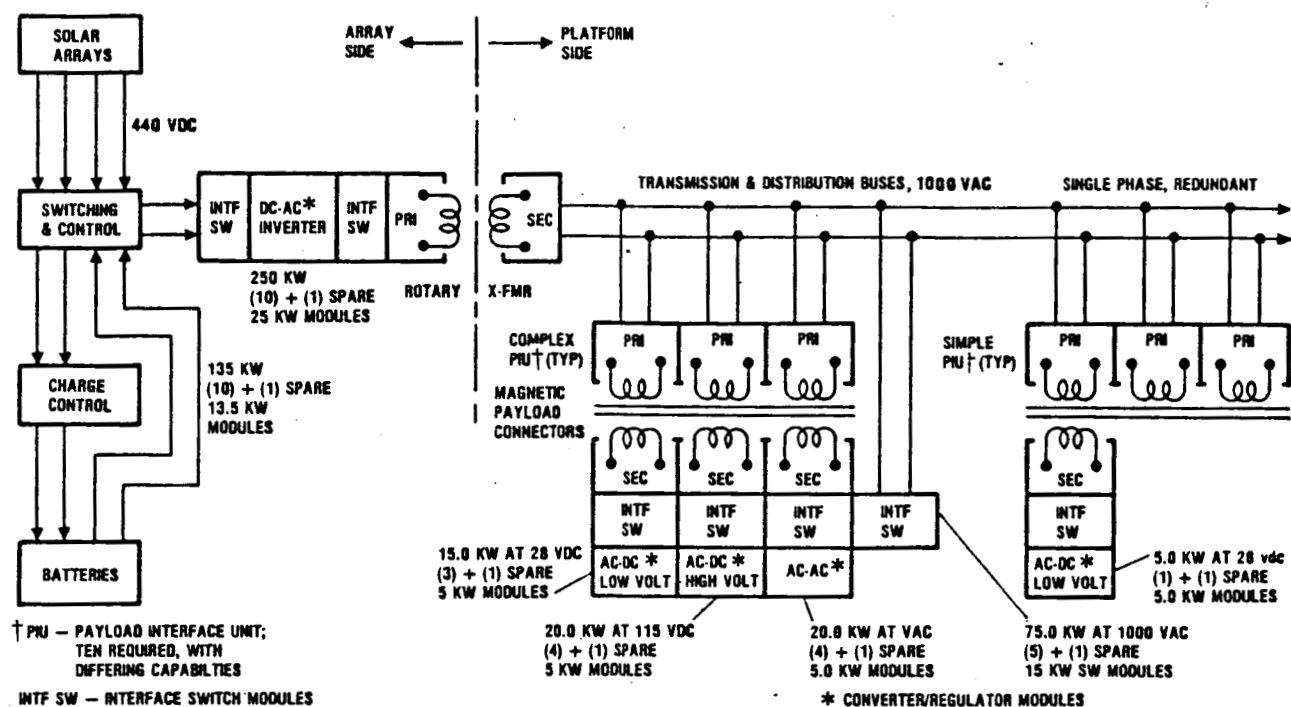


Figure 2-4. AC-DC hybrid resonant system block diagram.

maintenance and repair, and the related effects on other associated system hardware, such as solar arrays, batteries, and thermal management. Figures 2-5 and 2-6 show typical examples of the results of that optimization process for frequency and voltage, respectively. The system has the following major features:

- Hybrid (both centralized and distributed) regulations and control.
- Modular design and construction - sized for minimum weight/life-cycle-cost
- High voltage transmission (1000 VAC RMS)
- Medium voltage array ( $\leq 440$  VDC)
- Resonant inversion
- Transformer Rotary Joint
- High frequency power transmission power line ( $\geq 20$  KHz)
- Energy storage on array side of rotary joint
- Fully redundant
- 10-year life with minimal replacement and repair

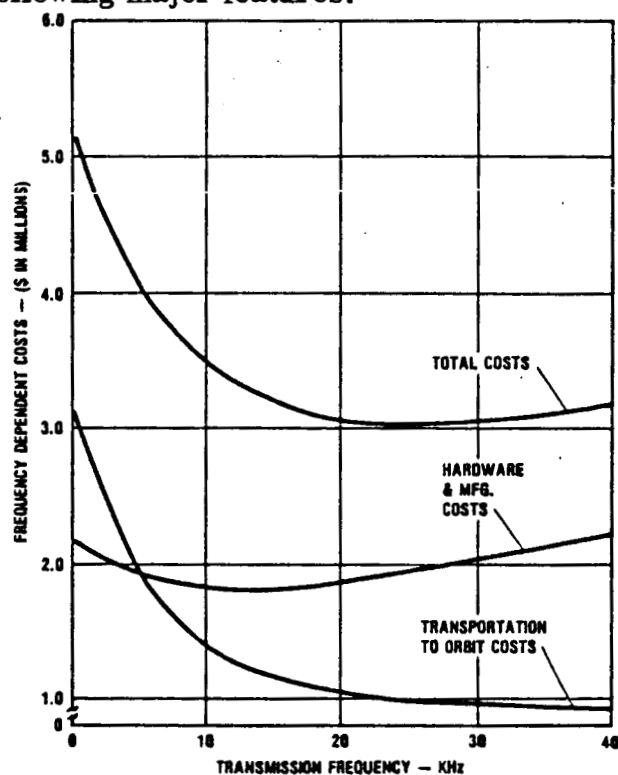
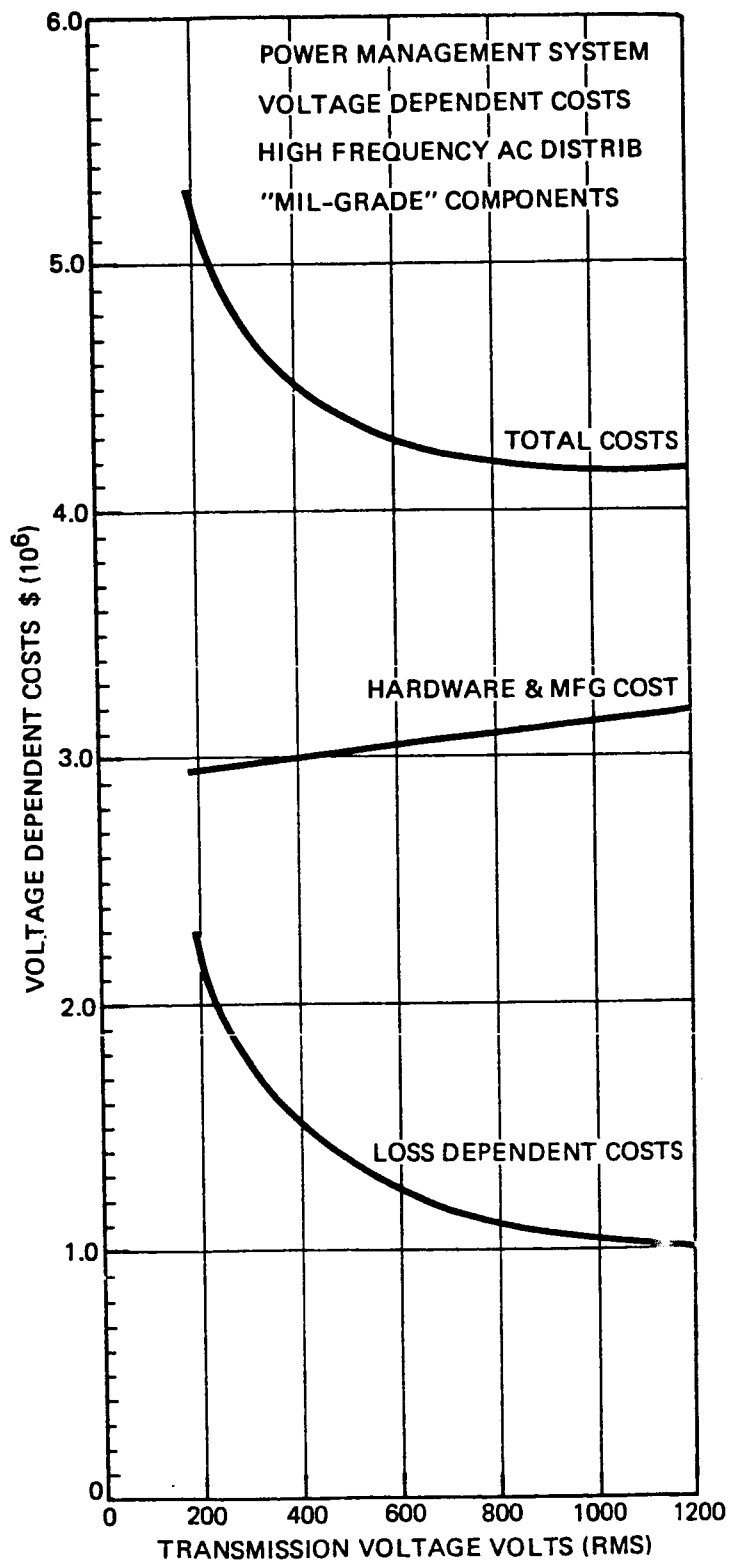
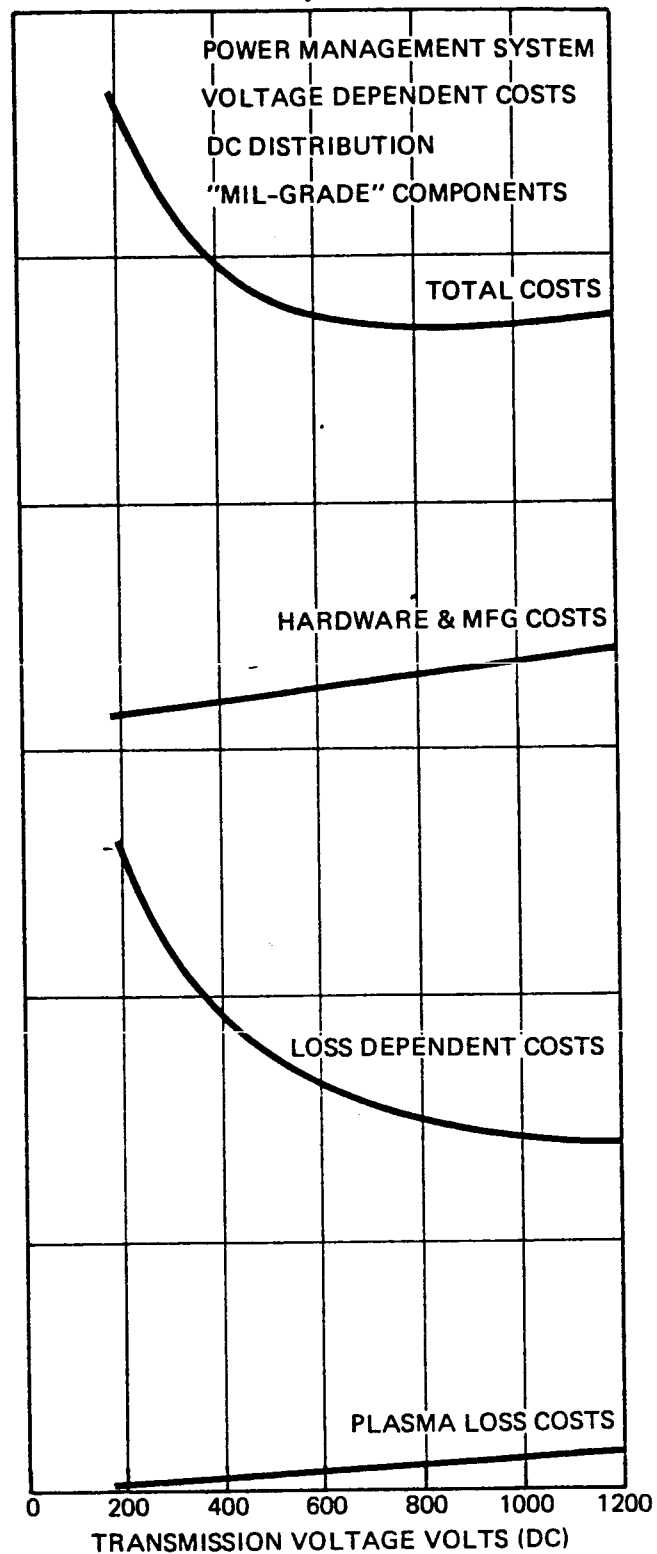


Figure 2-5. Power management system frequency dependent costs: high frequency AC distribution.



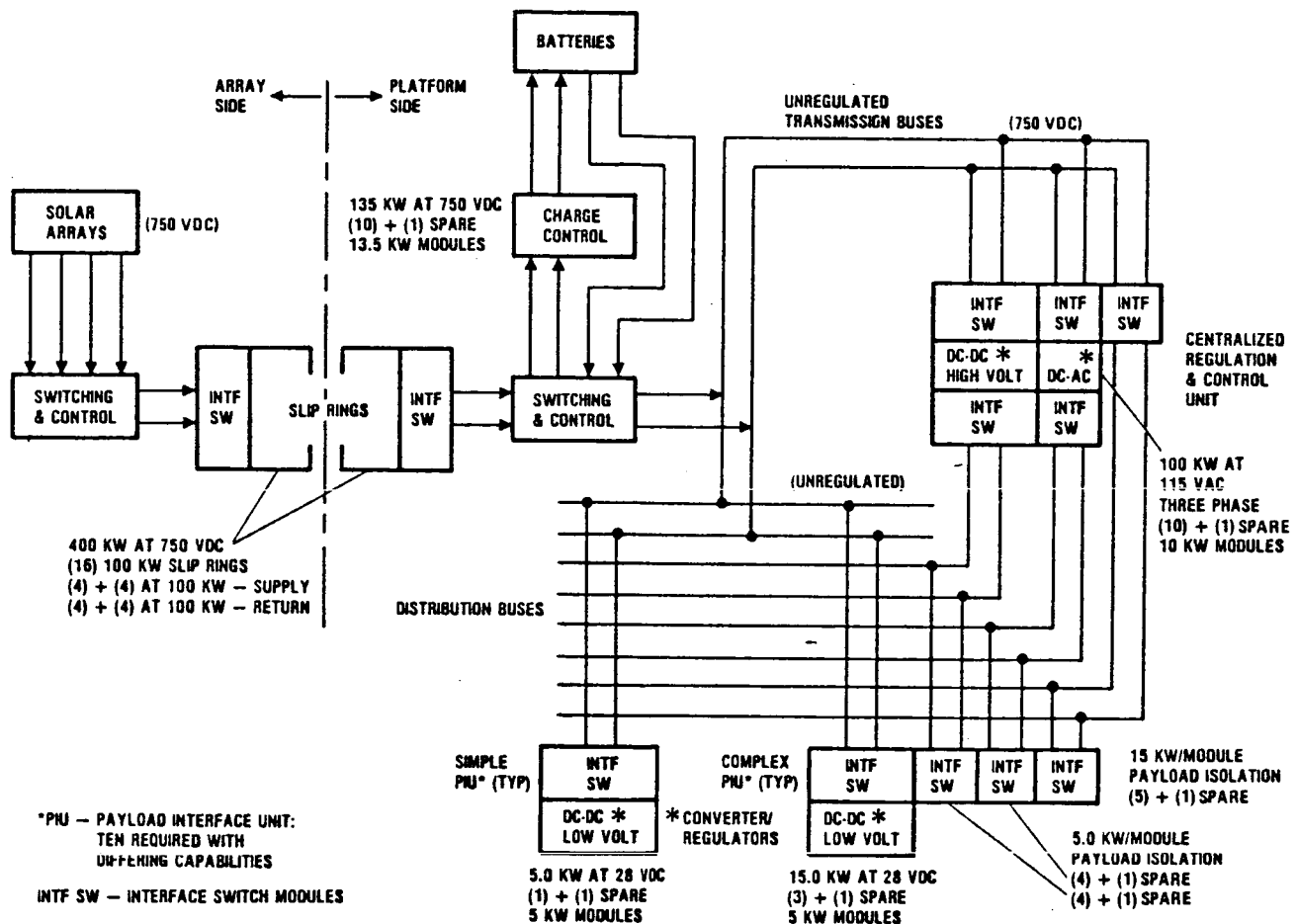
a. High frequency AC distribution



b. DC distribution

Figure 2-6. Power management system voltage-dependent costs.

Since DC would be a second choice for this application and could very well be a first choice in applications for other types of space vehicles and payloads, it is also necessary to consider technologies important to the development of DC systems. To that end, an alternate DC hybrid system has also been refined and optimized from the standpoint of minimum life cycle costs. It is pictured on Figure 2-7 and has the following major features:



**Figure 2-7. DC system block diagram.**

- a. Hybrid (both centralized and distributed) regulation and control
- b. Modular design and construction - sized for minimum weight/life-cycle-cost
- c. High voltage transmission, storage, and array (750 VDC)
- d. Fully redundant
- e. 10 year life through minimal replacement and repair
- f. Power system isolation must be provided by the payloads and users.

At this point, it is obvious to everyone who is acquainted with the AC-DC trade-offs historically performed on space power management systems that the above answer is a turn-around from the usual AC/DC conclusion, even considering the inherent technical and operational advantages of AC.



Generation methods notwithstanding, the terrestrial power companies have exploited the advantages of AC power and refined its methods and hardware for years. Recent radical improvements in conversion equipment have extended the versatility and improved efficiencies of those systems. Many of those features and advantages apply directly to space systems.

The ability to use transformers at interface points within a system allows for low-cost, simple, light-weight, reliable voltage level changes, power system isolation, load and source matching, and system expansion.

Transformer-like technology, which utilizes the ability of alternating current to transfer power through its varying magnetic field allows for the use of several types of noncontact devices, which help solve particularly thorny space system problems. Slip-rings used in the array-to-spacecraft rotary joint can be replaced by a rotating transformer. Power interconnections can be accomplished in a noncontact, insulated way using a magnetic connector conceived during this study. Rotating machinery can be powered by AC motors, eliminating noisy commutators and brushes.

AC systems are not as noisy as equivalent DC ones. Power turn-on and turn-off and load switching can be accomplished when the AC current passes through zero, thereby making the transient producing rate-of-change of current equal to zero during switching. In general, fundamental frequencies (20 KHz) are too low to act as interference sources and there are negligible harmonics. Furthermore, reasonable size external detectors do not respond to the low frequency fundamental.

Finally, high power AC equipment and piece-parts are readily available on a commercial level. In most cases, simple extrapolations of basic level terrestrial power hardware and/or space or military qualification is all that is required for uses supporting this kind of program. Conversely, piece parts and other basic forms of hardware to support multi-100 KW DC systems require extensive development.

Table 2-1 is a summary of the advantages and disadvantages of AC and DC systems.

In the past, traditional AC systems weighed and cost much more and were less efficient than DC systems with equivalent power. As desirable as they were, AC systems always lost out because of high life-cycle costs and payload penalties. Therefore, a new kind of AC system was needed.

The trade-offs and analyses performed during this study pointed the way to cost and weight-effective AC system design. High voltage (with its accompanying low current) improves efficiency through reduction of transmission and switching losses. High frequency reduces magnetic and energy storage component sizes. Low solar array and battery voltages improve reliability and reduce plasma interaction problems and losses.

Table 2-1. AC and DC system advantages and disadvantages.

- AC SYSTEM

- ▲ MAJOR ADVANTAGES

- a. HIGH DEGREE OF FLEXIBILITY FOR MEETING NEED OF DIFFERING USERS
    - b. SIMPLE POWER SYSTEM ISOLATION
    - c. REDUCED PLASMA LOSSES FOR LOW VOLTAGE ARRAY
    - d. COMPONENTS MORE MATURE
    - e. SIMPLIFIED STORAGE INTERFACE (FUEL CELLS AND BATTERIES)
    - f. GROWTH POTENTIAL
    - g. NON-CONTACT INTERFACES AND DEVICES POSSIBLE
    - h. NO INHERENT VOLTAGE CEILING

- ▲ MAJOR DISADVANTAGES: NONE

- ▲ ADDITIONAL DEVELOPMENT REQUIRED

- a. SYSTEM PROOF OF CONCEPT
    - b. SYSTEM DESIGN
    - c. HIGH FREQUENCY USER EQUIPMENT DEVELOPMENT
    - d. ULTRASONIC INTERFERENCE AND PLASMA COUPLING MUST BE EVALUATED

- DC SYSTEM

- ▲ MAJOR ADVANTAGES

- a. MATURE SYSTEM DESIGN
    - b. AC CONVERSION NOT REQUIRED

- ▲ MAJOR DISADVANTAGES

- a. USER INTERFACE FLEXIBILITY THROUGH COMPLEX HARDWARE
    - b. DIFFICULT POWER SYSTEM ISOLATION
    - c. HIGH ARRAY VOLTAGE TO MINIMIZE PMS LOSSES INCREASES PLASMA PROBLEMS
    - d. VOLTAGE CEILING OF APPROX 1000V
    - e. RUBBING CONTACT INTERFACES AND DEVICES

- ▲ ADDITIONAL DEVELOPMENT REQUIRED: HIGHER RATING COMPONENTS

Moving the batteries and their charge control hardware to a module on the array side of the rotary joint significantly reduces the amount of DC-to-AC inverter hardware.

Optimizing an AC system based on the considerations of the preceding paragraph is still not enough to make it competitive. The real key is a new, more creative approach to system design. When power system isolation and/or large level changes

are required in the power conversion and control hardware, a DC-DC converter is required. Recent developments in resonant converters have provided significant improvements in efficiency (from typicals below 90% up to 95%) for that process by eliminating the dynamic portion of switching losses. That large improvement makes resonant converters the logical choice for power processing in this type of system, whether they are used in their DC-DC, DC-AC, or cyclo-inverter embodiments.

The next logical step is the one that makes AC systems truly competitive with DC and the choice for this type of space platform application. The entire power system is designed as a single, distributed, resonant converter. A multi-module unidirectional, four-quadrant converter driving a resonant circuit, including the source and load transformers and power transmission busses, converts DC into high frequency AC (like the usual front half of any DC-DC converter). Unidirectional, four-quadrant converter modules are transformer-coupled to the transmission system at the load end to provide the loads with either DC or any frequency and format AC, depending on their individual requirements. (This end is equivalent to the load-end half of a DC-DC converter.) A typical multiple-driver, multiple-receiver system is shown on Figure 2-8. Gross modular parameters are noted on the drawing and the 'dash numbers' associated with the converter modules reflect variations on the basic four-quadrant module.

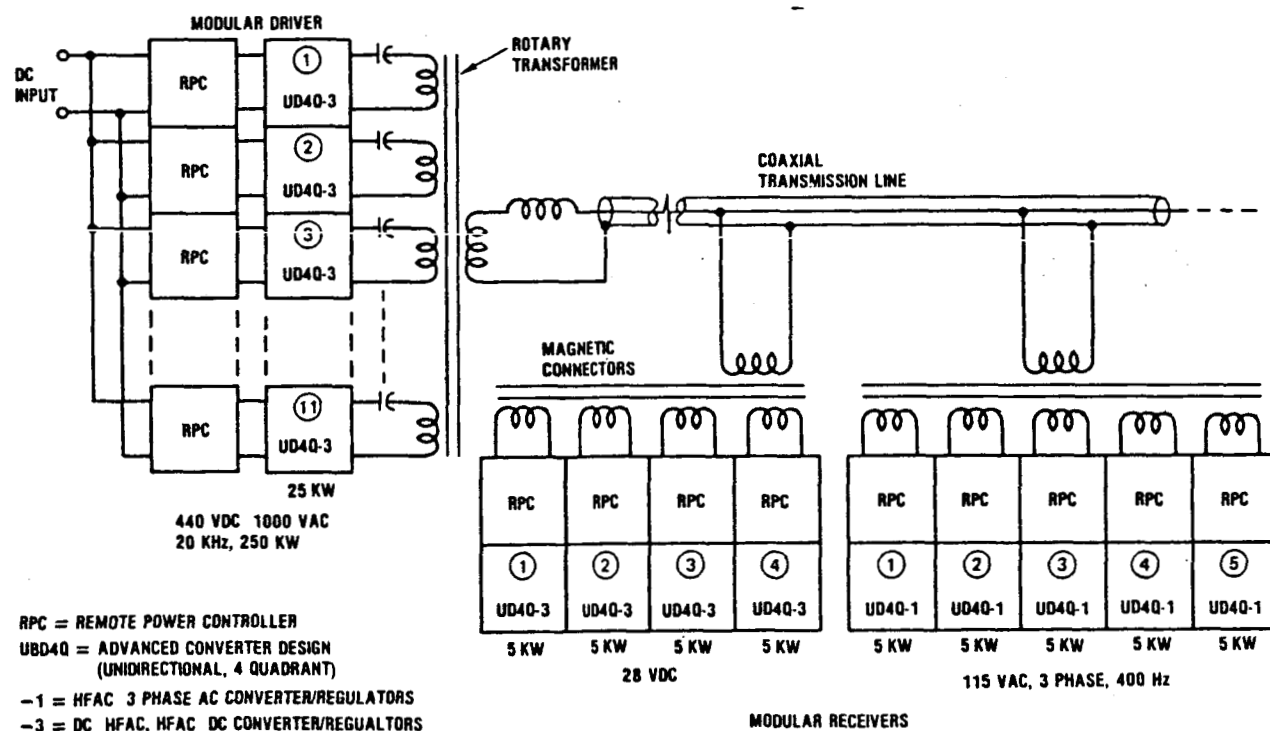


Figure 2-8. Modular, resonant AC power system.

The losses and efficiencies of the two study systems are about the same, even though the DC system seems to have less "in-line" conditioning hardware. The use of resonant converters in the AC system provides conversion efficiencies approaching 95%, as described above. Since the AC system is one large resonant converter, the driver (inverter), coupling (one transformer), receiver (converter) combination has an overall efficiency of about 95%. Additional losses in the rotary transformer, and the small losses in the high voltage line and RPCs provide for overall AC system efficiencies approaching 92 or 93%.

In the DC system, a compromise is drawn with regard to system voltage, balancing switching and transmission losses against plasma losses from the solar arrays. Adding these losses (which are larger than the AC case because of the nonoptimum operation of both the solar array and the distribution system) to regulator and converter losses results in an overall DC system efficiency which also approaches 92 or 93%.

Costs of four main system options have been evaluated by the study in detail and those results are summarized in Table 2-2.

Table 2-2. Costs for the primary system options.

SYSTEM	RESEARCH AND TECHNOLOGY COSTS	DESIGN	RECURRING COSTS (PROD. & OPER.)	LIFE CYCLE COSTS TOTALS
NON-ISOLATED DC SYSTEM (LOWEST COST DC)	\$2.3M	\$6.72M	\$6.52M	\$15.54M
*FULLY ISOLATED DC SYSTEM	2.4M	6.72M	10.28M	19.40M
CONVENTIONAL AC SYSTEM	2.0M	6.78M	11.53M	20.31M
*RESONANT, H.F. AC SYSTEM (RECOMMENDED)	3.0M	6.78M	7.11M	16.89M

CONCLUSION: FOR EQUIVALENT CAPABILITY SYSTEMS, (MARKED \*) THE  
RECOMMENDED AC SYSTEM COSTS \$2.51M LESS

The "non-isolated DC system" is the alternate system of the study. The "fully isolated" entry is an estimate which attempts to include the payload power system isolation hardware required by many users. The "conventional AC system" is a low frequency (400 hz), three phase, inverter/converter system with energy storage in the payload docking module. The "resonant, H.F. AC system" is the study-recommended system.

Recurring costs of the two study systems are equivalent to \$26.00 per peak watt for DC and \$28.00 per peak watt for AC.

### 2.3 TASK 2, TECHNOLOGY ADVANCEMENT

Examining system and component level requirements and comparing them with the state of the art has led to the conclusion that a 250 KW space power management system could be "brute force" designed with today's DC technology. However, if it is to be truly cost-effective, technological improvements are required during the next five to ten years. All of the key technologies identified can meet mid-to-late 1980s need dates if they are addressed in a timely manner.

The recommended AC system has technology gaps primarily in the proof-of-concept, system design, and high-level component areas. The alternate DC system has technology gaps primarily in the detailed component and piece-part areas where actual component design and maximum electrical performance and ratings must be improved. A detailed presentation of the necessary technologies to support system design, including rough costs and schedules, may be found in Volume 2.

Thermal considerations related to the PMS alone do not show any significant technology gaps. There are no significant technology gaps in mechanical design areas for power hardware in this size system.

Table 2-3 is a prioritized list based on cost/benefit of the technology developments requiring NASA funding, which are feasible and necessary to support the timely development of a cost-effective space power system for this application. Task 2 methodology is shown in Figure 2-9.

Table 2-3. Technology development priorities\*.

GROUP**	PRIORITY RANKING	TECHNOLOGY DEVELOPMENT
I	1.	Integrated "split" resonant DC-DC/DC-AC converter system development.
I	2.	Rotary transformer development.
I	3.	Payload connector development <ul style="list-style-type: none"> <li>a. AC, magnetic connector</li> <li>b. DC, high voltage, high current</li> </ul>
I	4.	Improved performance semiconductor switch elements <ul style="list-style-type: none"> <li>a. Improved ratings for power FETs</li> </ul>
I	5.	Coaxial transmission line development
I	6.	Remote Power Controller (RPC) improvement <ul style="list-style-type: none"> <li>a. Data/command interface</li> <li>b. Improved performance (voltage, current)</li> <li>c. Multi-pole, multi-throw configurations</li> <li>d. Incorporation of new devices</li> <li>e. Transient overload control</li> </ul>
II	7.	Plasma Characteristic Research <ul style="list-style-type: none"> <li>a. Special tests for irregular shapes/transmission lines/small components (AC and DC)</li> <li>b. AC energy coupled into the plasma as a function of voltage and frequency (AC)</li> <li>c. Expanded flat-plate testing for plates with voltage gradients (AC and DC)</li> <li>d. Arcing phenomena characterization (AC and DC)</li> <li>e. Surface damage through sputtering (AC and DC)</li> </ul>
II	8.	Optical data bus rotary joint
II	9.	Insulating materials with low dielectric loss
II	10.	Analysis of total platform dynamics
III	—	Assessment of high frequency power line impact on "standard" user equipment <ul style="list-style-type: none"> <li>a. Motors</li> <li>b. Power supplies</li> </ul>
III	—	New/updated EMI-EMC specifications for high frequency power systems
III	—	Thermal management system technology
III	—	Micrometeorite protection for insulated components
III	—	Space-qualified thyristors/triacs
III	—	Space-qualified slip rings for high power and data transmission

\*Priorities for important technology developments that NASA should sponsor in the early 1980s.

\*\*GROUP I Immediate start required  
 II Shorter lead time will allow later start  
 III Necessary items, non-critical start times

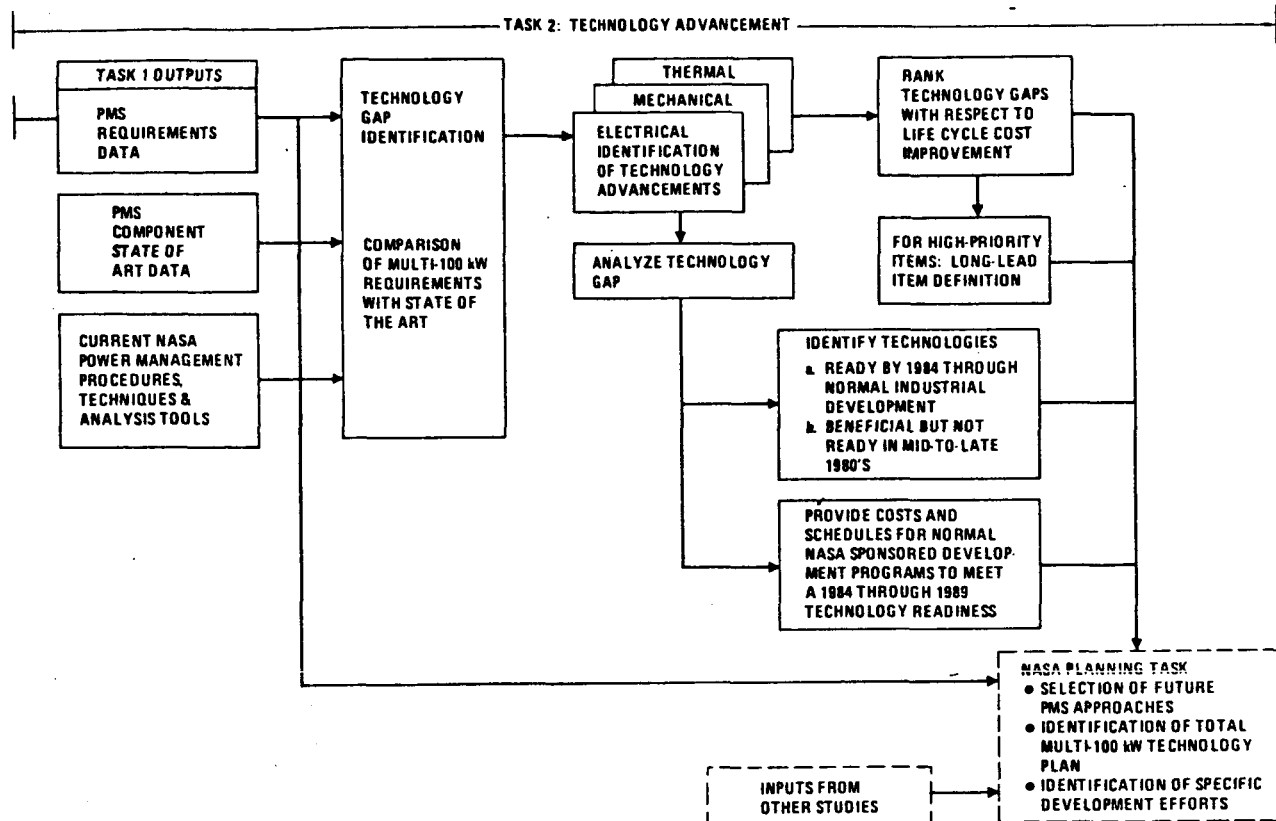


Figure 2-9. Task 2 methodology.

# 3

## CONCLUSIONS

A DC to AC to AC/DC high-frequency system with hybrid regulation and control could provide the best cost-effective approach to power management for this type of general-purpose platform, operating in low earth orbit, in the power range between 100 and 250 KW. This system has a significant number of technical and operational advantages as compared to DC systems.

An all-DC system is a reasonable second choice and has applications in spacecraft with fixed loads, less versatility, fewer payload variables, and different demands and parameters. Technologies in support of DC should be developed along with those unique to AC. Future missions will thereby be able to choose a cost-effective approach suited to their individual requirements.

The design of cost-effective power management systems in the multi-100 KW range requires development of supporting technology as described above, listed in Table 2-3, and detailed in Volume 2. With the appropriate government/industry emphasis on normal development programs, all the key technologies needed to support AC or DC systems will meet mid-to-late 1980s need dates.



# 4

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